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THE INFLUENCE OF CONSTRUCTIVE CHARACTERISTICS OF THE TROMBE WALL ON EFFICIENCY OF PASSIVE HEATING SYSTEM

A passive solar heating system with Trombe wall with natural air circulation is considered for a one-storey well-insulated apartment house with an area of 150 m². The heat energy consumption for heating without Trombe wall for the city of Kyiv was 59.7 kWh / (m² year), for Odesa - 50.4 kWh / (m² year). In EnergyPlus software package, a mathematical modeling of the heating load in the building was performed with changing the geometric characteristics of the Trombe wall (the thickness of the air gap between the glass and heat-absorbing wall, the thickness of the massive wall) for Kyiv and Odesa. Optimum values of the thickness of the air layer between the glass packet and the heat absorbing wall were 0.03-0.04 m for Kyiv, 0.025-0.035 m for Odesa; the thickness of the massive wall, depending on its material, was: made from cellular concrete – 0.35-0,4 m, from bricks – 0.35-0,4 m and claydite concrete – 0.25-0.3 m during minimum thermal load of the building. The influence of the filler (air or argon), the type of glass (conventional, k-glass, i-glass) and the type of a glazing unit (single-chamber or double-chambered windows) on the loss of thermal energy into the environment is considered. It is recommended to use a double-glazed window filled with argon with the energy-saving i-glass – 4M-4M-16Ar-16Ar-I4. The using of the Trombe wall allows to reduce the heating load for Kyiv – 14.7%, for Odessa – 16.3%. Payback period of the passive Trombe wall is amounted to: for heat pump systems – 10 years and 4 months, for a system with electric boiler – 2 years and 10 months in Kyiv; for Odesa – 9 years and 2 years and 8 months, respectively.

Keywords: passive heating system, Trombe wall, the coefficient of efficiency, solar radiation, energy-saving glass.

Introduction

Today problems regarding energy efficiency are becoming acute, especially for home heating. A high tariff on cost of heat energy encourages consumers to look for ways of using it more economical by improving the efficiency of existing heating systems in buildings.

In cold climates the amount of useful solar energy reaching the earth in winter is more than the daily requirement for heating in a well-insulated building, and the sun is virtually inexhaustible source of energy [1]. However, there are three main problems limiting the possibility of using this energy source:

- the biggest amount of solar energy is coming during the least desired in heating season;
- low density of solar radiation requires the use of large surfaces for its collection;
- solar energy has daily and seasonal fluctuations that are intensified in connection with changes in the weather.

Passive systems are known and have been used since long ago. Heat is transferred through the building's enclosing and accumulating structures, or through air or water. Buildings which use passive systems require major source of heat and serve only to save fuel resources. In practice, those buildings are still rare, due to the lack of sufficient information about their effectiveness.

Trombe wall is related to passive systems of indirect sunlight capture, which includes a massive wall of transparent thermal glazing and external air gap between them.

Solar heat passing through glass during the day is absorbed by the dark surface of the wall, and slowly carries the warmth inside by a massive wall with a delay in time. The wall serves as a heat accumulator, and stays warm at night. The high degree of transparency of the glass increases the flow of heat to the massive wall.

Total volume of the wall, or in other words the amount of accumulation, should be sufficient to store solar energy received per day, but not too large, as in this case the temperature difference between the internal temperature of the room and temperature of accumulating walls decreases, which accelerates cooling of the wall and increases heat loss.

The accumulated energy is transferred into the building for room heating. The efficiency of heating or cooling facilities depends on the thermal conductivity of solid walls and parameters of convective flow in the air gap and in the space of the room. Normative maximum value of the specific annual energy consumption of one-storey building is 120 kWh / (m² year) for the I temperature zone (Kyiv city) and 110 kWh / (m² year) for the II temperature zone (Odesa city) [2].

In [3] ideal Trombe wall thickness is 0.3m of concrete for cities located on the northern latitude of 37-40 degrees. The average temperature of the inner wall surface during the heating season was 21 ºC, and outer wall temperature was changing from 10 to 60 ºC, depending on the incoming solar radiation on the surface of the wall.

In [4] experimental studies of Trombe wall sized 3.9 m x 3.55 m with five holes sized 0.25 m x 0.25 m at the bottom and the top for air circulation with a single layer glass glazing with extended buffer zone of 1.2 meters width were carried out. The construction of the wall is designed for short-term accumulation of heat on the part of the buffer zone to avoid significant radiation losses from the wall at night. Temperature of the brick wall in early May reached 46 ºC, floor –58 ºC. During the working time the room connected to the wall received around 2 kWh of heat per square meter of the wall. The highest air velocity in the holes was 1.6 m / s, and the efficiency of the system was about 0.5-0.6.

Aim of the article

Purpose of the work – to determine the impact of design characteristics: the thickness of the air gap between the glass and heat-absorbing wall, thickness and material of massive wall with minimal thermal load, depending on the location of the building in the climatic conditions of Ukraine.

The influence of wall materials, insulating glass type and thickness of the air layer between the glazing and the absorbing wall on characteristics of the Trombe wall for heating buildings was studied.

Material and research results

Calculations were carried out in software EnergyPlus package [5], which allows to use climatic data from two cities of Ukraine – Kyiv and Odesa. Program file IWEC (International Weather for Energy Calculations) contains typical weather files suitable for use in modeling of energy processes.

As a model, a well-insulated single-storey house of 150 m^2 with passive Trombe wall with natural air circulation heating system was considered. The thermal resistance of the building envelope was: exterior walls – 4.17 m^2K / W; windows – 0.73 m^2K / W; doors – 3.03 m^2K / W; floor – 4.87 m^2K / W; roof – 5.32 m^2K / W. Consumption of thermal energy for heating without Trombe wall for Kyiv city was 59.7 kWh / (m^2 year), for Odesa – 50.4 kWh / (m^2 year). The internal temperature in the building was 20 ºC.

Heat accumulating wall with area of 17.5 m^2 is painted black. At the top and the bottom of the wall five circulation holes with an area of 0.15 m^2 are installed (Fig. 1). The optimum size and area of the holes is defined on the basis of studies that are shown in [6]. As the external glazing, single-or double-glass window was used. The thickness of the air layer between the glass wall and heat-surface varied from 0.013 m to 0.08 m. The wall was south-orientated with sun canopy of 0.75 m, to reduce overheating in summer.

To maximize the efficiency of passive heating system the optimal ratio between the geometrical characteristics of Trombe walls were determined: air layer thickness between the glass and heat absorbing wall and the thickness of massive walls for the three materials: cellular concrete, brick, claydite concrete.

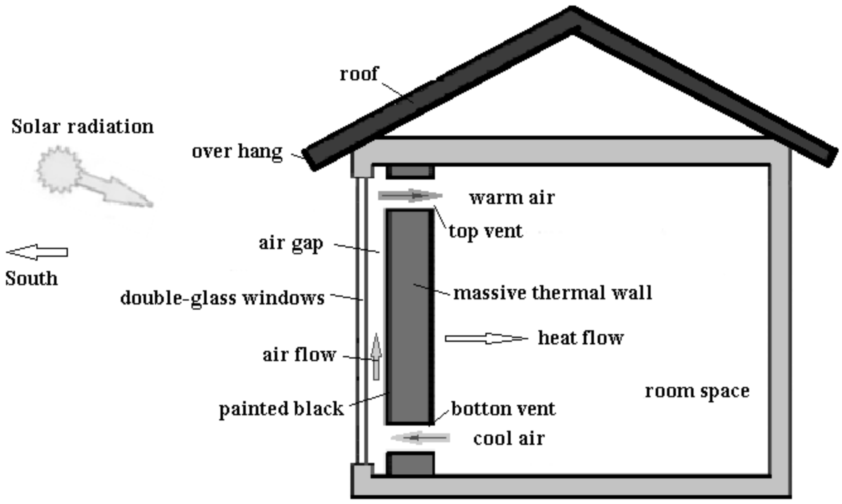

Figure 1 – Model of the building with Trombe wall

The effectiveness of the Trombe wall was evaluated by the number of the lowest possible energy consumption per unit area of the house, which follows from the heat balance.

Calculations were carried out taking into account the incoming solar radiation during the day for each month of the heating season in Kyiv and Odesa for buildings of the same type. The modeling process revealed that the efficiency of the southern region is 10% higher than the north [7].

Figure 2-3 shows the results of the simulation to determine the cost of heat for heating depending on the geometrical characteristics of the Trombe wall for different cities of Ukraine.

Simulation results allowed to determine the optimum parameters for Trombe wall in Kyiv and Odesa (see Tab. 1).

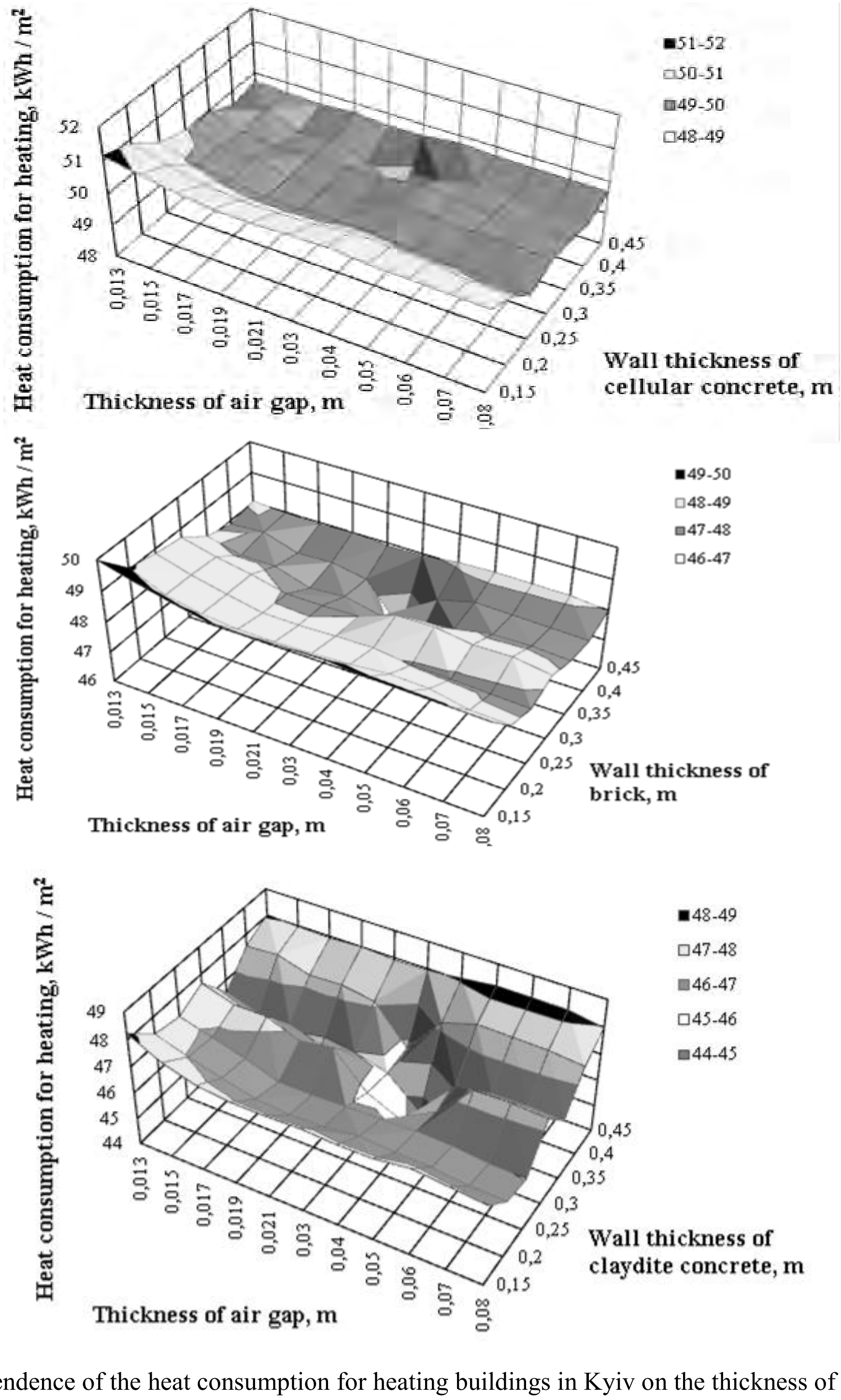

Figure 2 –Dependence of the heat consumption for heating buildings in Kyiv on the thickness of the air layer and the thickness of the walls at its various materials

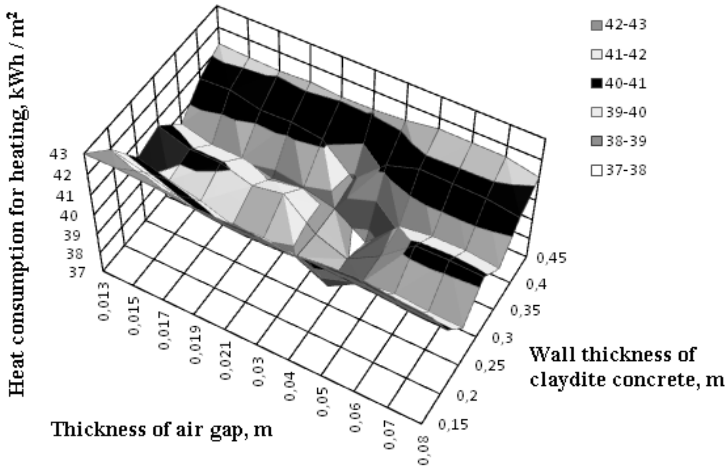

Figure 3 – Dependence of heat consumption for heating in Odesa on the thickness of the air layer and the thickness of the wall of claydite concrete

Table 1– Optimal parameters of Trombe wall for Kyiv and Odesa

	Material type walls		
	cellular concrete	brick	claydite concrete
	Kyiv		
Wall thickness, m	0.4	0.35	0.3
Air gap thickness, m	0.03	0.04	0.04
Heat consumption for heating, kWh/m^2 year	47.9	46.2	44.7
	Odesa		
Wall thickness, m	0.35	0.4	0.25
Air gap thickness, m	0.04	0.04	0.04
Heat consumption for heating, kWh/m^2 year	40.6	40.3	37.6

As the table shows, the optimum thickness of the air layer is 0.04 meters for almost all cases.

With a daily amount of the total solar energy of 3.5 MJ / m^2 at average conditions of cloudiness in Kiev in January the average temperature of air in the layer was 21 ºC, and the velocity of its movement – 0.028 m / s. The temperature in the room was 12 °C with an outside temperature of - 6 ºC. These temperatures confirm the need for installation of additional energy sources for heating.

The optimum wall thickness depends on the material and the city location of buildings (amount of solar radiation). For cities located at latitude 46-50 degrees the Trombe wall thickness is 0.25-0.4 m depending on the material of the wall. The most effective material for Trombe wall is claydite concrete, which reduces the cost of heat for heating buildings by 20%.

The Trombe wall leads to overheating in the summer months (see Fig. 3). To avoid overheating during daytime the sliding panels and sun-covering devices are installed, and they are opened at night to intensify the heat losses to the environment.

Figure 4 shows that during the heating season the effective angle of the canopy arrangement can be considered as the angle of 60 degrees. In the application of this inclination angle, sunlight will fall on the wall of the receiver in full extent, as the angle of direct sunlight during heating period for Kyiv ranges from 16.3 to 43.5 degrees, and in Odesa from 20 to 47.5 degrees [8].

To reduce the costs of heating in winter the canopy should be minimized or removed, if it's allowed by the design of the building.

Forced air circulation in mid-air layers of the room increases the intensity of heat transfer.

To reduce losses through the glass parts of the walls of passive design the influence of filler, the type of glass and glass type number on the required energy for heating and cooling was analyzed.

In the analysis ordinary glass windows and energy saving windows were applied (Fig. 5):

- k- glass Low-E glass with "hard" energy-saving coating;
- i-glass Double Low-E glass with "soft" energy-saving coating.

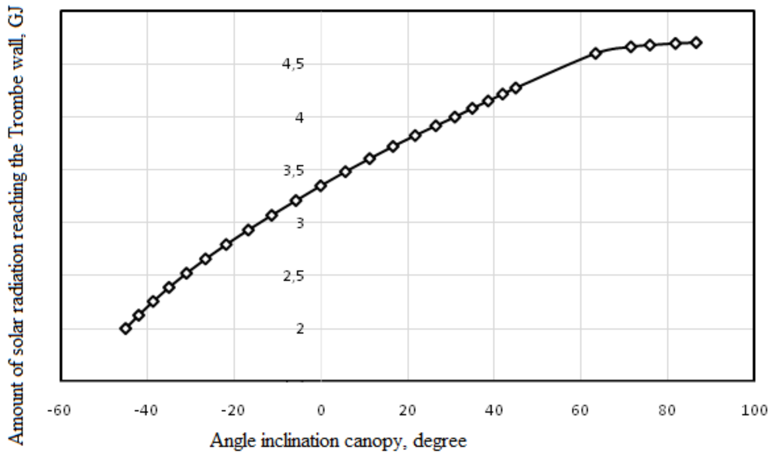

Figure 4 – Dependence of the amount of solar radiation that comes to the surface of Trombe wall from the protective canopy installation angle ("+" above the horizontal plane, "–" below the horizontal plane)

Figure 5 shows that single-chamber glazing filled with inert gas store more energy than those that are filled with air in the case of ordinary glass at 0.8%, k-glass and 2.8% of the i- glass-and at 3.5%. Compared with the difference is: ordinary glass – 1%; k-glass – 3.3% and i-glass – 6.1%.

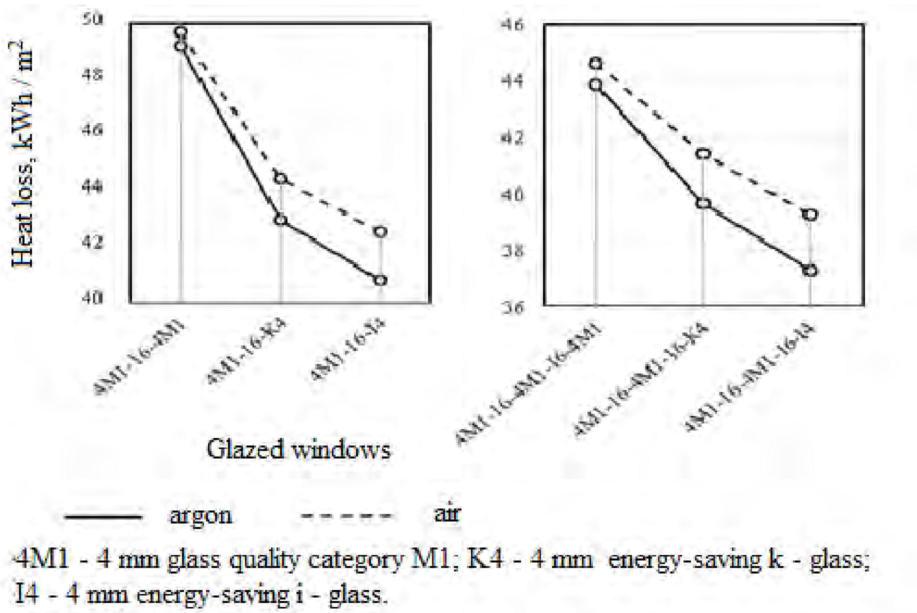

Figure 5 – Requirements for building heating in Kyiv with single-chamber and double-glass windows

The use of double-glass windows filled with inert gas argon and use of selective coating allows to reduce heat loss through the glass envelope for 18-20%. It should be taken into account that for double-glass window (4M-4M-16Ar-16Ar-I4) total solar energy transmittance is 0.50, the coefficient of heat transfer resistance is 0.8 m^2K / W, and for single-chamber (4M-16-M4), 0.78 and 0.32 respectively [9]. This leads to decrease in thermal efficiency of Trombe wall due to less solar radiation incoming and reduce in heat loss through the glass envelope by increasing the thermal resistance.

In [7] the annual heat replacement rate for building heating using Trombe wall passive solar system was determined for Kyiv – 14.7%, for Odesa – 16.3% by the procedure [10]. The lowest value is the replacement rate in January.

The economic feasibility of using Trombe walls in combined heating systems using heat pump or electric boiler as the main heat source was considered in [11].

Payback period of passive Trombe walls amounted to: for heat pump systems – 10 years and 4 months, for a system with electric boiler – 2 years and 10 months in Kyiv; for Odesa – 9 years and 2 years and 8 months, respectively.

Conclusions

1. For this building configuration it is advisable to use passive heating from the Trombe wall made of claydite concrete with thickness of 0.3 m for Kyiv and of 0.25 m for Odesa and with air layer of 0.04 m. The heat consumption for heating is 45- 45.5 kWh / (m^2 year) and 37-38 kWh / (m^2 year), respectively.

2. The use of double-glass windows made of i-glass leads to lower thermal efficiency of Trombe wall because of decreasing the incoming solar radiation and reducing the heat loss through the glass envelope by 18-20% by increasing the thermal resistance.

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ВПЛИВ КОНСТРУКТИВНИХ ХАРАКТЕРИСТИК СТІНИ ТРОМБА НА ЕФЕКТИВНІСТЬ ПАСИВНОЇ СИСТЕМИ ОПАЛЕННЯ

Розглянута пасивна система сонячного опалення зі стіною Тромба з природною циркуляцією повітря для одноповерхового добре утепленого житлового будинку площею 150 $м^2$. Витрата теплової енергії на опалення без стіни Тромба для м. Києва становила 59,7 кВт·год /($м^2$ рік), для Одеси – 50,4 кВт·год ($м^2$ рік). У програмному пакеті EnergyPlus проведено математичне моделювання опалювального навантаження будівлі при зміні геометричних характеристик стіни Тромба (товщини повітряного прошарку між склопакетом і теплопоглинальною стінкою, товщини масивної стіни) для

Києва і Одеси. Оптимальні значення товщини повітряного прошарку між склопакетом і теплопоглинальною стінкою для Києва дорівнюють 0,03-0,04 м, для Одеси –0,025-0,035 м; товщини масивної стіни в залежності від її матеріалу становили: з дірчастого бетону – 0,35-0,4 м, з цегли – 0,35-0,4 м і керамзитобетону – 0,25-0,3 м при мінімальному тепловому навантаженні будівлі. Розглянуто вплив наповнювача (повітря або аргон), виду скла (звичайне, k-скло, i-скло) і типу склопакета (однокамерний або двокамерний) на втрати теплової енергії в навколишнє середовище. Рекомендовано використання двокамерного склопакета заповненого аргоном з енергозберігаючого i-скла – 4M-4M-16Ar-16Ar-I4. Використання стіни Тромба дозволяє зменшити опалювальне навантаження в Києві на 14,7%, а в Одесі на – 16,3%. Термін окупності пасивної стіни Тромба становив: для системи з тепловим насосом 10 років і 4 місяці, для системи з електричним котлом – 2 роки і 10 місяців для Києва, а для Одеси – 9 років і 2 роки і 8 місяців, відповідно.

Ключові слова: пасивна система опалення, стіна Тромба, коефіцієнт ефективності, сонячна радіація, енергозберігаюче скло.

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ВЛИЯНИЕ КОНСТРУКТИВНЫХ ХАРАКТЕРИСТИК СТЕНЫ ТРОМБА НА ЭФФЕКТИВНОСТЬ ПАССИВНОЙ СИСТЕМЫ ОТОПЛЕНИЯ

Рассмотрена пассивная система солнечного отопления со стеной Тромба с природной циркуляцией воздуха для одноэтажного хорошо утепленного жилого дома площадью 150 м^2. Расход тепловой энергии на отопление без стены Тромба для г. Киева составлял 59,7 кВт·ч/(м^2 год), для Одессы – 50,4 кВт·ч/(м^2 год). В программном пакете EnergyPlus проведено математическое моделирование отопительной нагрузки здания при изменении геометрических характеристик стены Тромба (толщины воздушной прослойки между стеклопакетом и теплопоглощающей стеной, толщины массивной стены) для Киева и Одессы. Оптимальные значения толщины воздушной прослойки между стеклопакетом и теплопоглощающей стенкой для Киева равнялись 0,03-0,04 м, для Одессы –0,025-0,035 м; толщины массивной стены в зависимости от ее материала составили: из дырчатого бетона – 0,35-0,4 м, из кирпича – 0,35-0,4 м и керамзитобетона –0,25-0,3 м при минимальной тепловой нагрузке здания. Рассмотрено влияние наполнителя (воздух или аргон), вида стекла (обычное, k-стекло, i-стекло) и типа стеклопакета (однокамерный или двухкамерный) на потери тепловой энергии в окружающую среду. Рекомендовано использование двухкамерного стеклопакета заполненного аргоном из энергосберегающего i-стекла – 4M-4M-16Ar-16Ar-I4. Использование стены Тромба позволяет уменьшить отопительную нагрузку в Киеве на 14,7 %, а в Одессе на – 16,3%. Срок окупаемости пассивной стены Тромба составил: для системы с тепловым насосом 10 лет и 4 месяца, для системы с электрическим котлом – 2 года и 10 месяцев для Киева, а для Одессы – 9 лет и 2 года и 8 месяцев, соответственно.

Ключевые слова: пассивная система отопления, стена Тромба, коэффициент эффективности, солнечная радиация, энергосберегающее стекло.

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